REVISED ANL-REPORTED TENSILE DATA FOR V-Ti AND V-Cr-Ti ALLOYS*

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SUMMARY

The tensile data for all irradiated vanadium alloy samples and several unirradiated vanadium alloys tested at Argonne National Laboratory (ANL) have been critically reviewed and revised, as necessary. The review and revision are based on re-analyzing the original load-displacement strip-chart recordings using a methodology consistent with current ASTM standards. No significant difference has been found between the newly-revised and previously-reported values of yield strength (YS) and ultimate tensile strength (UTS). However, by correctly subtracting the non-gauge-length displacement and linear gauge-length displacement from the total cross-head displacement, the uniform elongation (UE) of the gauge length decreases by 4-9% strain and the total elongation (TE) of the gauge length decreases by 1-7% strain. These differences are more significant for lower-ductility irradiated alloys than for higher-ductility alloys.

PROGRESS AND STATUS

Introduction

The results of tensile tests performed at Argonne National Laboratory (ANL) on unirradiated and irradiated V-Ti and V-Cr-Ti alloys have been reported in tabular and/or graphical form in the Fusion Reactor Materials Semiannual Progress Reports from the periods ending March 31, 1987 (DOE/ER-0313/2) to June 30, 1996 (DOE/ER-0313/20). Results can also be found in the open literature, but the Progress Reports contain the most detailed set of results for the tensile properties of interest: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). Recently, the methodology used to determine the UE and TE values has come into question. In the process of resolving the issue of whether tensile-machine displacement was properly subtracted from cross-head displacement in determining elongations, all tensile properties have been re-examined in the current work. Both published and unpublished load-displacement curves have been re-analyzed and re-evaluated to derive the revised set of tensile properties.

The one-third-size tensile specimens (SS3) used in all ANL tensile tests (except for the oxidation studies) have a gauge length of 7.62 mm and a cross-sectional area of about 1 mm^2 (0.9-1.4 mm^2). The Instron testing machine has a 500 kgf (4900 N) load cell. A uniform cross-head speed of 0.5 mm/minute was used for all tests, giving an effective gauge-length strain rate of 0.11%/second. Based on data in laboratory notebooks and on the original load-displacement curves, the load cell was varied during the tests from a full vertical scale (250 mm in height) of anywhere from 10 kgf to 250 kgf. Useful data for most tests were recorded with a full scale of 50 kgf for unirradiated material and 100 kgf for irradiated material. In terms of converted stress, this amounts to about 4 MPa per vertical grid mark. The strip chart recording speed was generally 50 mm/minute, although 100 mm/minute was used in several cases. At 50 mm/minute, each horizontal grid mark corresponds to a cross-head displacement of 0.02 mm and a gauge length strain of 0.262%. In general, the extensometer readings for cross-head displacement at the end of the test were consistent with the values determined from cross-head displacement rate and strip-chart recorder speed rate. For the oxidation studies, the gauge section of the samples is 19 mm in length, about 4.5 mm in width and about 1 mm in thickness. The reference gauge-length strain rate for the oxidized and unoxidized samples is 0.018%/second.

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The terminology and the methodology for analyzing tensile data from strip-chart recordings is established in ASTM Designation E 6 and E 8, respectively.[1] It is worthwhile to review these terms and methods. For monotonically increasing load vs. displacement curves up to the maximum load, YS is the load (divided by the initial gauge cross-sectional area) corresponding to an offset strain of 0.2% (displacement at zero load divided by the initial gauge length). The offset value of 0.2% has no intrinsic significance. It is based on practicality and experience in analyzing tensile curves. The offset strain is determined by "analytically" or "graphically" unloading the specimen at a linear load-displacement slope corresponding to the effective linear portion of the load-displacement curve. The intersection of this line with the horizontal axis determines the offset displacement and strain. While various methods (e.g., initial tangent modulus, tangent modulus, secant modulus and chord modulus) are given in the ASTM standards, the methodology used in the current work corresponds more closely to the tangent modulus approach. With most of the load-displacement curves for vanadium alloys tested in the ANL Instron machines exhibiting an elongated "S" shape during the low-strain rise in load, the modulus is determined by the tangent line coinciding with the most number of points in the elongated part of the S-shape. Some of the load-displacement curves analyzed exhibit discontinuous yielding which consists of a rise to a high load (upper yield point, UYP) followed by a drop in load to a minimum value (lower yield point, LYP) followed by a rise in load with displacement up to the maximum load. For these cases, the 0.2% offset stress has little meaning. For consistency, the stress corresponding to the minimum yield point is designated as YS in the current work for samples which exhibit discontinuous yielding.

The UTS is relatively straightforward to determine. For monotonically increasing load with displacement up to the maximum load, the UTS is simply the maximum load divided by the initial gauge cross-sectional area. In the case of discontinuous yielding, the UYP may represent a higher load than for the continuous part of the curve after the discontinuous yielding. In such cases, the UYP is not to be used in determining UTS. The offset displacement (or strain) corresponding to the peak load (or UTS) is called the uniform elongation (UE). While UTS can be uniquely determined, more uncertainty is involved in determining UE, particularly for cases for which the maximum load is nearly constant over a displacement (or strain) range. While the ASTM standards imply that the midpoint of this flat region should be used to determine UE, the maximum offset strain corresponding to the maximum load is used in the current work. This decision is based on detailed analyses of stainless steel stress-strain curves and the criteria for necking. The maximum strain at peak load is more characteristic of the uniform elongation of the gauge section prior to necking.

The total elongation (TE) corresponds to the offset strain just prior to failure. The same slope as is used in the determinations of YS and UE is used to determine the offset displacement and strain at failure.

Results

About 100 tensile-test strip chart recordings have been re-analyzed for V-Ti and V-Cr-Ti alloys irradiated in FFTF. An additional four recordings have been re-analyzed for V-Cr-Ti alloys irradiated in HFIR. The difference between revised and previously-reported values of YS is on the order of ±10%. Much of this difference lies within the uncertainty of interpreting YS from load-displacement curves which exhibit discontinuous yielding. Some of the difference arises from the use of a different slope to determine the offset strain. The remaining differences have to do with uncertainty in interpreting results with changes in the strip-chart load scale. In any case, the ±10% is well within the uncertainties involved in determining YS and within the heat-to-heat variation for most structural alloys. The agreement between revised and previously reported values for UTS is even better (±1% deviation). This is not surprising given the relative simplicity and lack of ambiguity in determining the peak load and dividing it by the initial cross-sectional area. With regard to the uniform and total elongations, the average slope of the linearized-portion of the load-displacement curve is about 1.6 kN/mm, giving an average effective modulus of about 115 MPa/%. When the effective modulus for each load/displacement or stress/strain trace is used to determine the permanent offset UE and TE values, the revised values for UE and TE are lower by 4 - 9% strain for UE and 1 - 7% strain for TE than the previously reported values. The significance of these corrections increases as the irradiation/test temperature decreases and the ductility (UE and TE) of the vanadium alloys decreases.

The vanadium alloys in the unirradiated condition have higher ductilities (UE and TE) than those in the irradiated condition. Data from about 200 tensile-tested, unirradiated vanadium alloys have been reported previously in the literature. During the current reporting period, about 30 of the original tensile strip-chart recordings were located and re-analyzed. Based on the 30 cases analyzed, similar differences between revised and previously-reported YS, UTS, UE and TE values have been observed for the unirradiated cases as were observed for the irradiated cases. However, for the 30 cases analyzed. the vanadium alloys retain significant ductility even after the corrections have been made to UE and TE.

Discussion

Tensile properties of structural materials are significantly different than inherent material properties such as Young's modulus and Poisson's ratio. The test results for YS, UTS, UE and TE are dependent on sample size and shape, sample preparation, strain rate, test environment, as well as the methodology used to interpret the test data. The tensile properties generated within this R&D program do not constitute a "design data base" because of the small gauge length (7.62 mm) and the lack of repetition of tests under the same nominal conditions. For example, ASME specifications for pressure vessel material establish minimum values of YS, UTS and TE based on a two-inch (51 mm) gauge length for the shape of samples used in this R&D program. For most ductile materials which fail by local necking, TE decreases as the gauge length increases. Rather, the tensile data base is intended to be used in conjunction with other mechanical properties tests (e.g., Charpy, fracture-toughness, creep, fatigue, etc.) to compare the performance of different vanadium alloys, as well as the differences among the same nominal chemical composition with different impurity levels and microstructures. In order for the comparison to be meaningful, however, it is important that each party generating tensile data use the same terminology and methodology with regard to determining and reporting values for YS, UTS, UE, and TE. This is essential to the selection and optimization efforts within the vanadium alloy R&D program. Consistent with this rationale, the tensile properties reported by ANL for all irradiated samples and some unirradiated samples have been critically reviewed, and revised as needed, based on a combination of ASTM standards and knowledge of material performance. While standards such as those established in ASTM do not give a unique method for determining tensile properties and are somewhat naive with regard to material science considerations, the important aspect of a comparative program is to select and use a consistent and physically-realistic methodology. This implies using some common sense in applying standards, rather than blindly appling such standards. The following example illustrates this point.

The following discussion is contained in ASTM Ref. 1 (page 20) under **modulus of elasticity**:

"The stress-strain relations of many materials do not conform to Hooke's law throughout the elastic range, but deviate therefrom even at stresses well below the elastic limit. For such materials the slope of either the tangent to the stress-strain curve at the origin or at a low stress, the secant drawn from the origin to any specified point on the stress-strain curve, or the chord connecting any two specified points on the stress-strain curve is usually taken to be the 'modulus of elasticity.' In these cases, the modulus should be designated as the 'tangent modulus,' the 'secant modulus,' or the 'chord modulus,' and the point or points on the stress-strain curve described...."

This ASTM discussion may have some practical value in interpreting tensile data from strip-chart recordings, but it has little meaning with regard to material science and performance. Many structural materials (e.g., ferritic steels, stainless steels, vanadium alloys) have well-defined elastic moduli and elastic regimes which can be determined by dynamic methods. However, because of a variety of factors associated with the tensile test (e.g., machine stiffness and slip, the manner of gripping, the shape and size of the sample, etc.), the low-strain rise in load is more "S" shaped than linear and the effective modulus used to determine YS, UE and TE has little to do with the elastic modulus of the material. It is often at least an order of magnitude less than Young's modulus.

FUTURE WORK

Complete the re-analysis of the original load-displacement strip-chart recordings for unirradiated samples of vanadium alloys.

Issue a detailed report containing YS, UTS, UE and TE (and RA where available) tensile results for unirradiated and irradiated vanadium alloys tested at ANL, including sample identification number, neutron damage level, helium content, irradiation temperature and test temperature.

Re-evaluate trends in tensile data for vanadium alloys, particularly decrease in ductility with increase in strength due to increased Cr, Ti and Si levels, impurity levels, microstructure, and neutron-damage/helium-content.

REFERENCE

1. 1996 Annual Book of ASTM Standards, Section 3: Metals Test Methods and Analytical Procedures, Volume 03.01: Metals -- Mechanical Testing; Elevated and Low-Temperature Tests; Metallography; Designation E 6 (Standard Terminology Relating to Methods of Mechanical Testing, pp 17-26) and Designation E 8 (Standard Test Methods for Tension Testing of Metallic Materials, pp 55-96), ASTM, West Conshohocken, PA.